Approximate Transformations as Mutation Operators

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CCF-1566363, CCF-1629431,
CCF- 1652517, CCF-1703637,
and CCF-1704790

Motivation

Mutation Testing

- **Goal:** Technique that evaluates the quality of test suites

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- **How:** Introduces small syntactic change to the program
- **Example:**

```
x = x + 1
```

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Approximate Computing

- **Goal:** Technique that trades accuracy for performance

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for (i=0; i<n; i=i+1)
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for (i=0; i<n; i=i+2)
```

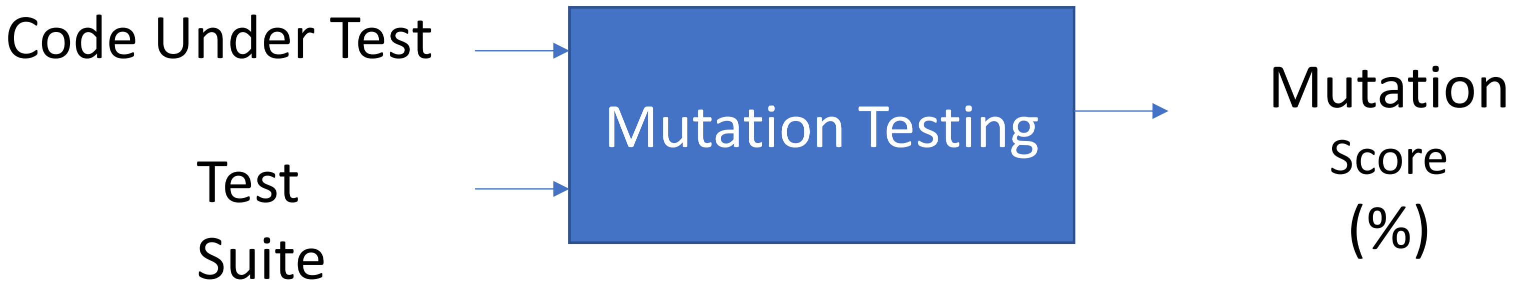
Vision

- To provide insights, mutation testing needs:
  - Varied mutation operators
  - High quality mutation operators

- We propose Approximate Transformations (ATs) as a new class of mutation operators leading to different program behaviors

Background: Mutation Testing

- Definition: Mutation testing is a technique for evaluating the quality of test suites



Code Under Test

Test Suite

Mutation Testing

Mutation Score (%)

STEPS OF MUTATION TESTING

01

MUTANT GENERATION

02

RUNNING THE TEST SUITE TO DETERMINE KILLED MUTANTS

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MUTANT GENERATION

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RUNNING THE TEST SUITE TO DETERMINE KILLED MUTANTS

Vectorz Mutation Example

```
public void swapRows(int i, int j) {
 if (i == j) return;
 int a = i * cols;
 int b = j * cols;
 int cc = columnCount();
 for (int k = 0; k < cc; k++) {
  int i1 = a + k;
  int i2 = b + k;
  double t = data[i1];
  data[i1] = data[i2];
  data[i2] = t;
} }
```

Vectorz Mutation Example

```
public void swapRows(int i, int j) {
  if (i == j) return;
  int a = i * cols;
  int b = j / cols;
  int cc = columnCount();
  for (int k = 0; k < cc; k++) {
    int i1 = a + k;
    int i2 = b + k;
    double t = data[i1];
    data[i1] = data[i2];
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 } }
```

STEPS OF MUTATION TESTING

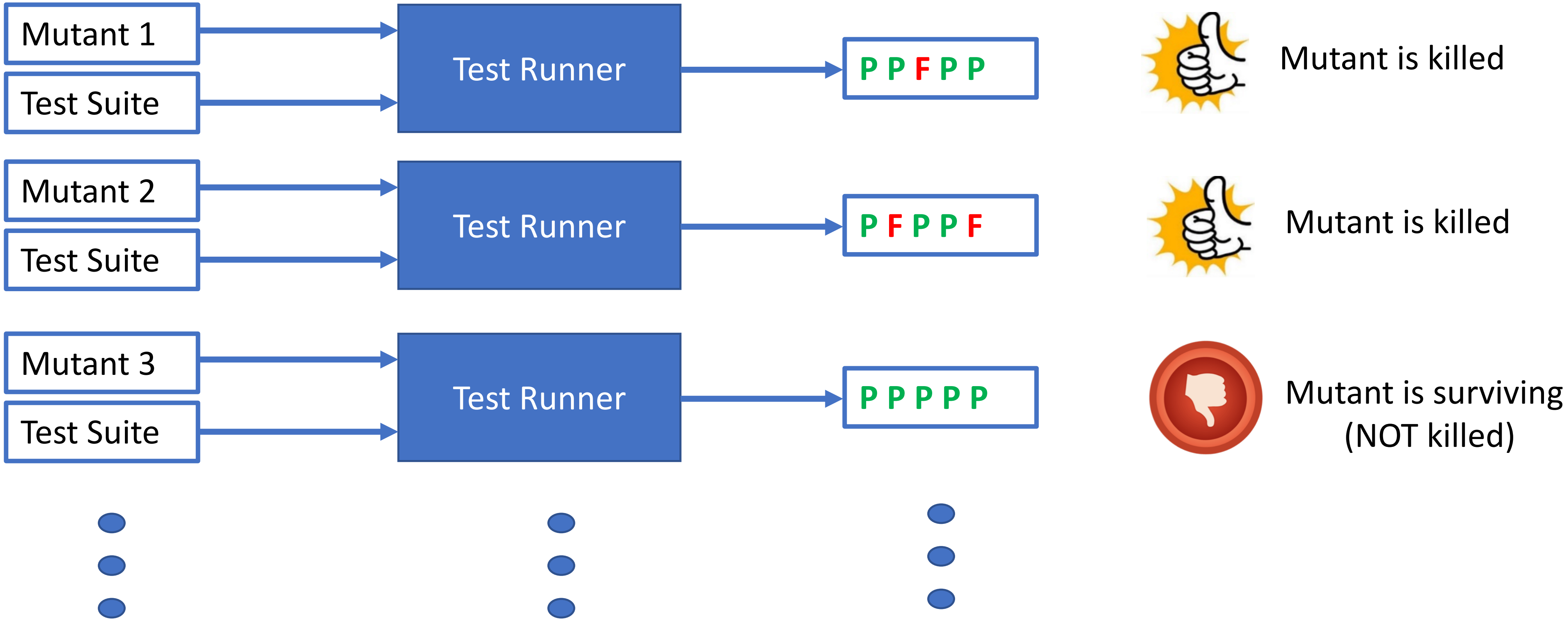
01

MUTANT GENERATION

02

RUNNING THE TEST SUITE TO DETERMINE KILLED MUTANTS

Running The Test Suite Outcomes



Mutant 1

Test Suite

Test Runner

P P F P P

Mutant is killed

Mutant 2

Test Suite

Test Runner

P F P P F

Mutant is killed

Mutant 3

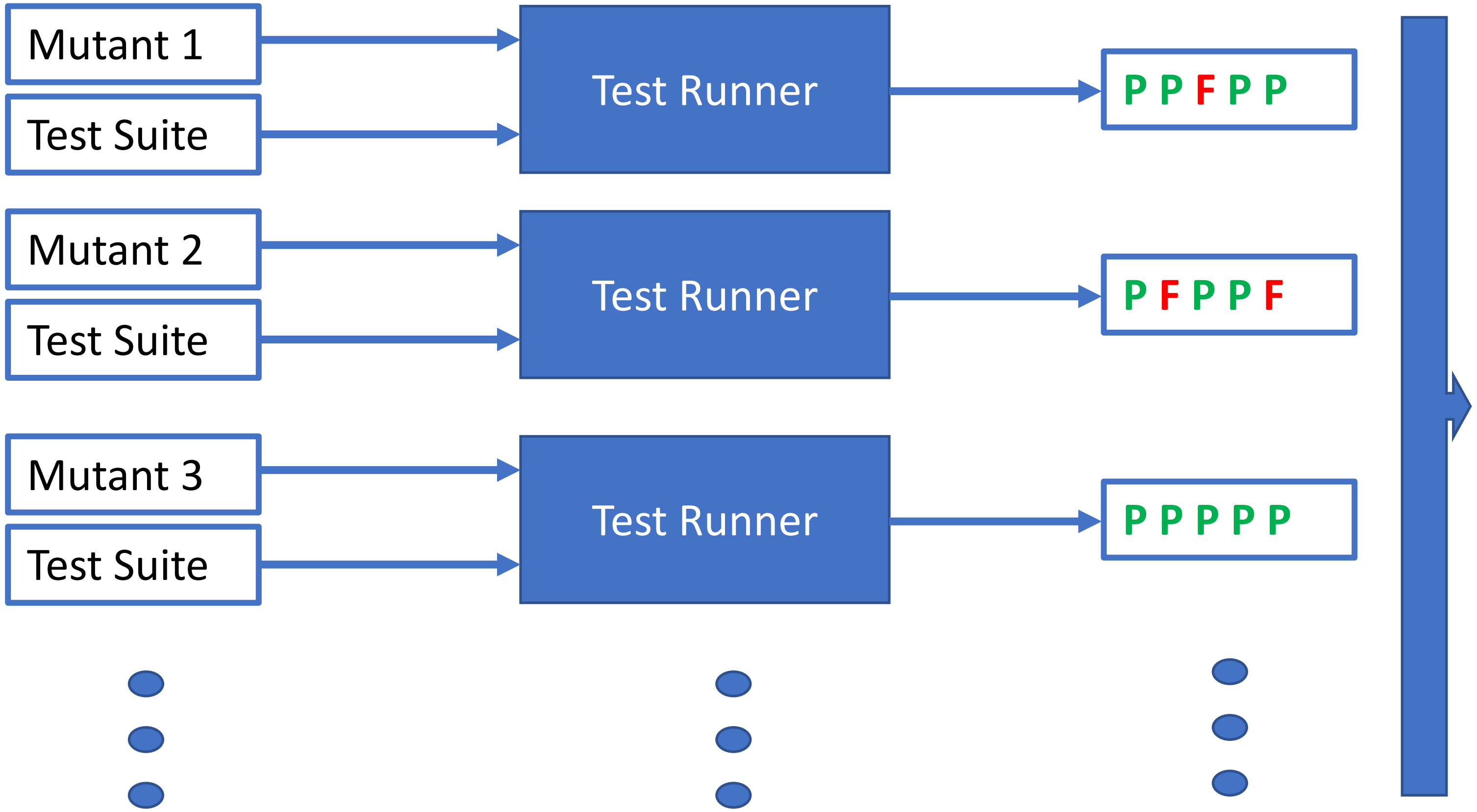
Test Suite

Test Runner

P P P P P

Mutant is surviving (NOT killed)

Mutation Score Computation



$$mutation\ score(\%) = \frac{killed\ mutants}{all\ generated\ mutants}$$

Vectorz Killed Mutant Example

```
public void swapRows(int i, int j)
{
 if (i == j) return;
 int a = i * cols;
 int b = j / cols;
 int cc = columnCount();
 for (int k = 0; k < cc; k++) {
  int i1 = a + k;
  int i2 = b + k;
  double t = data[i1];
  data[i1] = data[i2];
  data[i2] = t;
} }
```

```
private void doSwapTest(AMatrix m) {
if ((m.rowCount()<2)||(m.columnCount()<2)) return;

m=m.clone();
AMatrix m2=m.clone();
m2.swapRows(0, 1);
assert(!m2.equals(m));
m2.swapRows(0, 1);
assert(m2.equals(m));
...}
```

Vectorz Killed Mutant Example

```
public void swapRows(int i, int j)
{
 if (i == j) return;
 int a = i * cols;
 int b = j / cols;
 int cc = columnCount();
 for (int k = 0; k < cc; k++) {
  int i1 = a + k;
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...}
```

Mutant is killed

Background: Approximate Transformations

- Semantic changing transformations
- Trade accuracy for performance
- Big popularity in research recently
  - Machine learning, multimedia, data mining, …
- Example Transformations:
  - Integer to short precision degradation
  - Loop perforation

Vectorz Precision Degradation Example

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 if (i == j) return;
 int a = i * cols;
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 for (int k = 0; k < cc; k++) {
  int i1 = (short) (a + k);
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Integer to short precision degradation

Vectorz Precision Degradation Example

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Vectorz Loop Perforation Example

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Loop Perforation

Vectorz Loop Perforation Example

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👎 Mutant is NOT killed

Research questions

- **RQ1** How effective are ATs as mutation operators, compared to conventional mutation operators?
- **RQ2** What code patterns do ATs as mutation operators reveal?
- **RQ3** How can ATs as mutation operators help software testing practice?

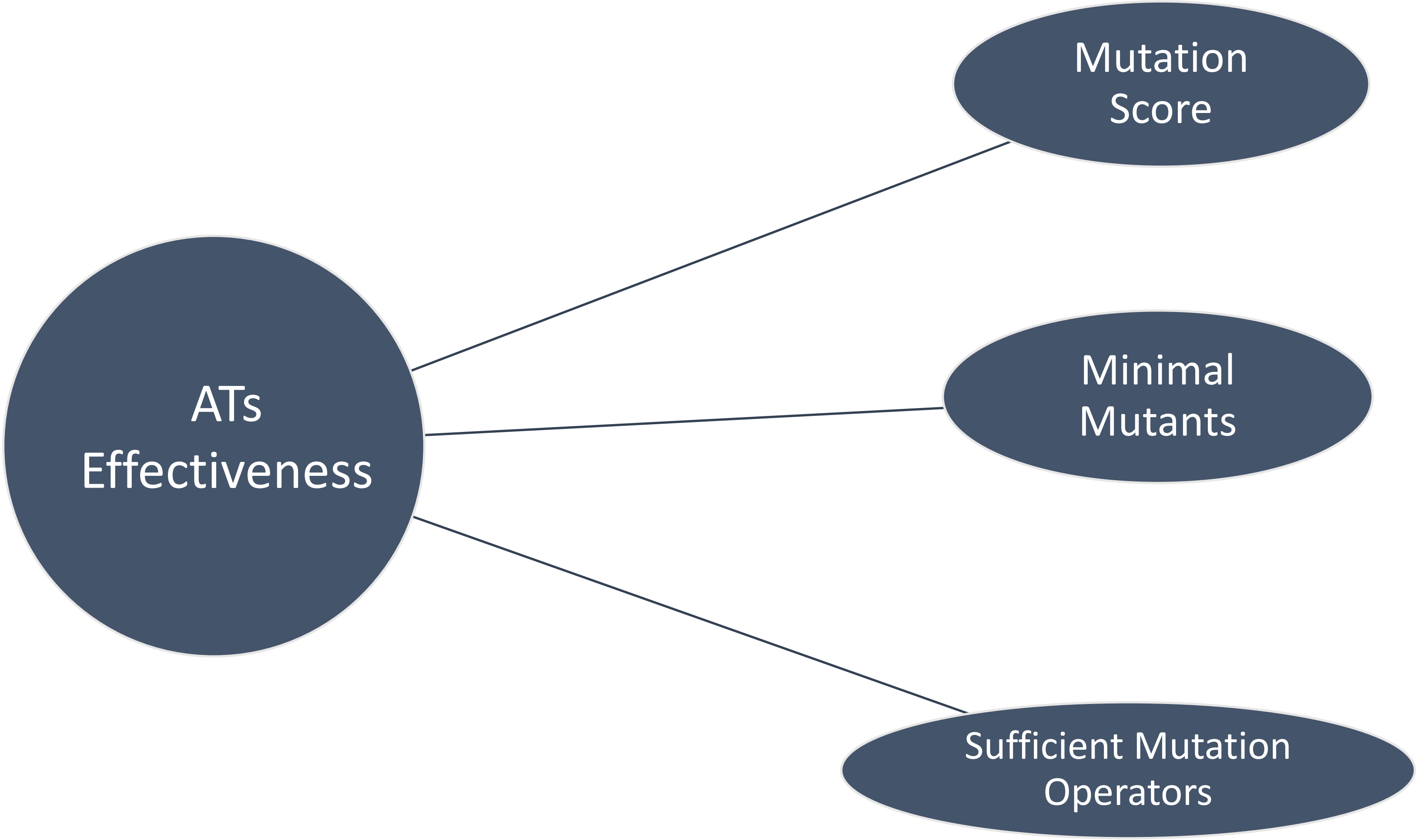
Experimental Setup

- We perform our study on 3 ATs
  - Loop Perforation (LPM)
  - Double To Float Precision Degradation (DTF)
  - Integer To Short Precision Degradation (ITS)
- Implement them as an extension to the PIT framework
- We compare against 14 PIT operators on 9 Open Source Java projects

RQ1:

How effective are ATs as mutation operators, compared to conventional mutation operators?

Quantitative Analysis



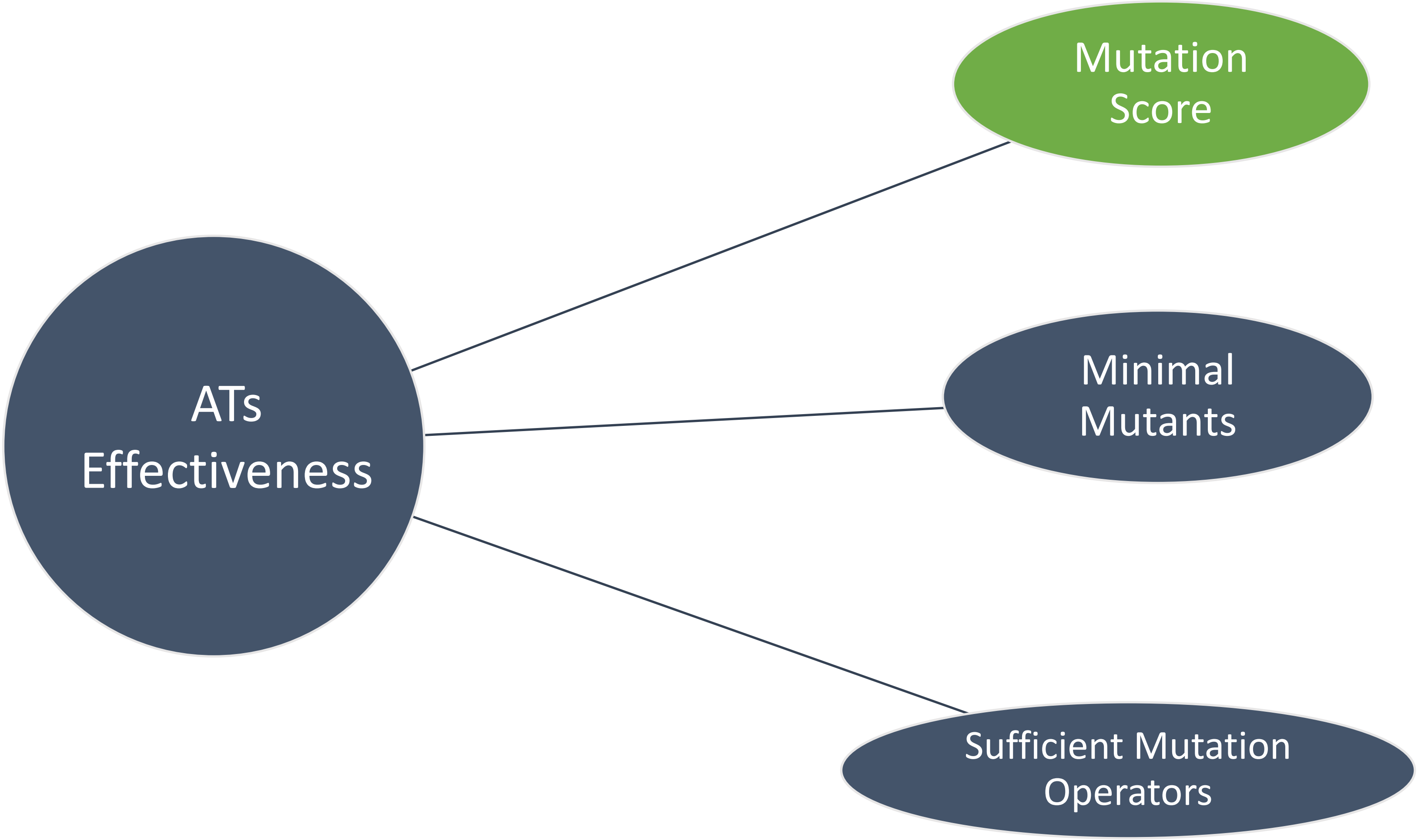
ATs Effectiveness

Mutation Score

Minimal Mutants

Sufficient Mutation Operators

Quantitative Analysis



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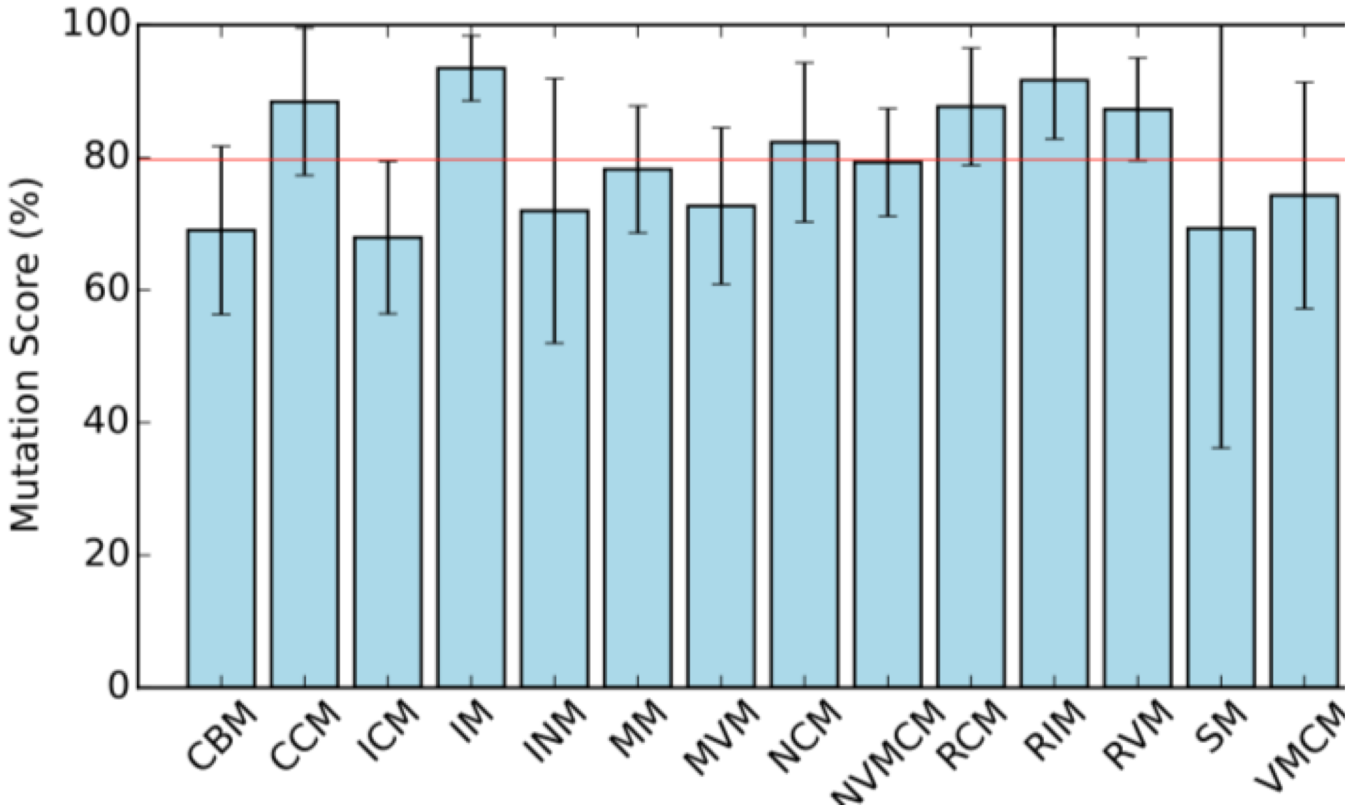
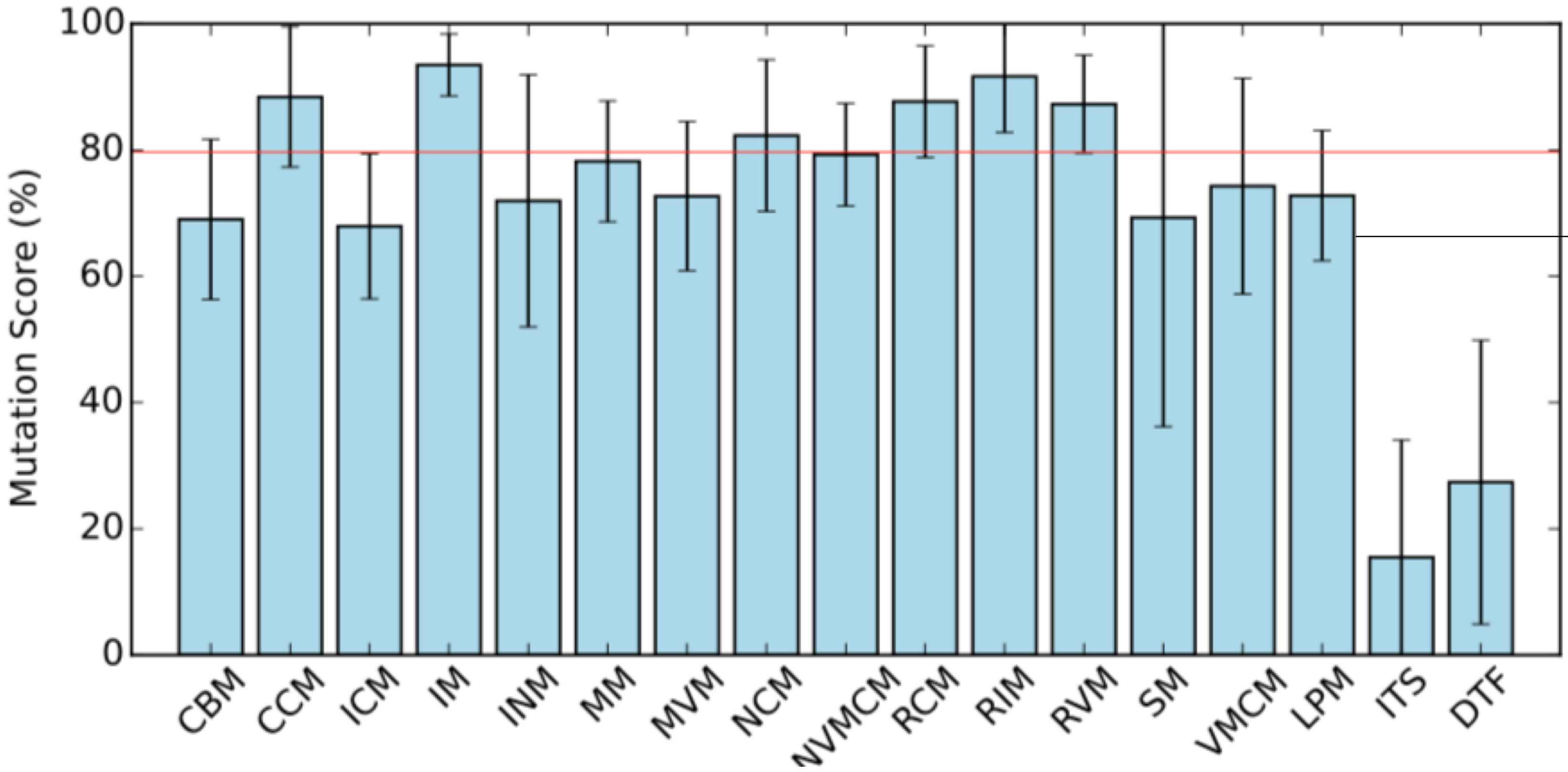


79.65%

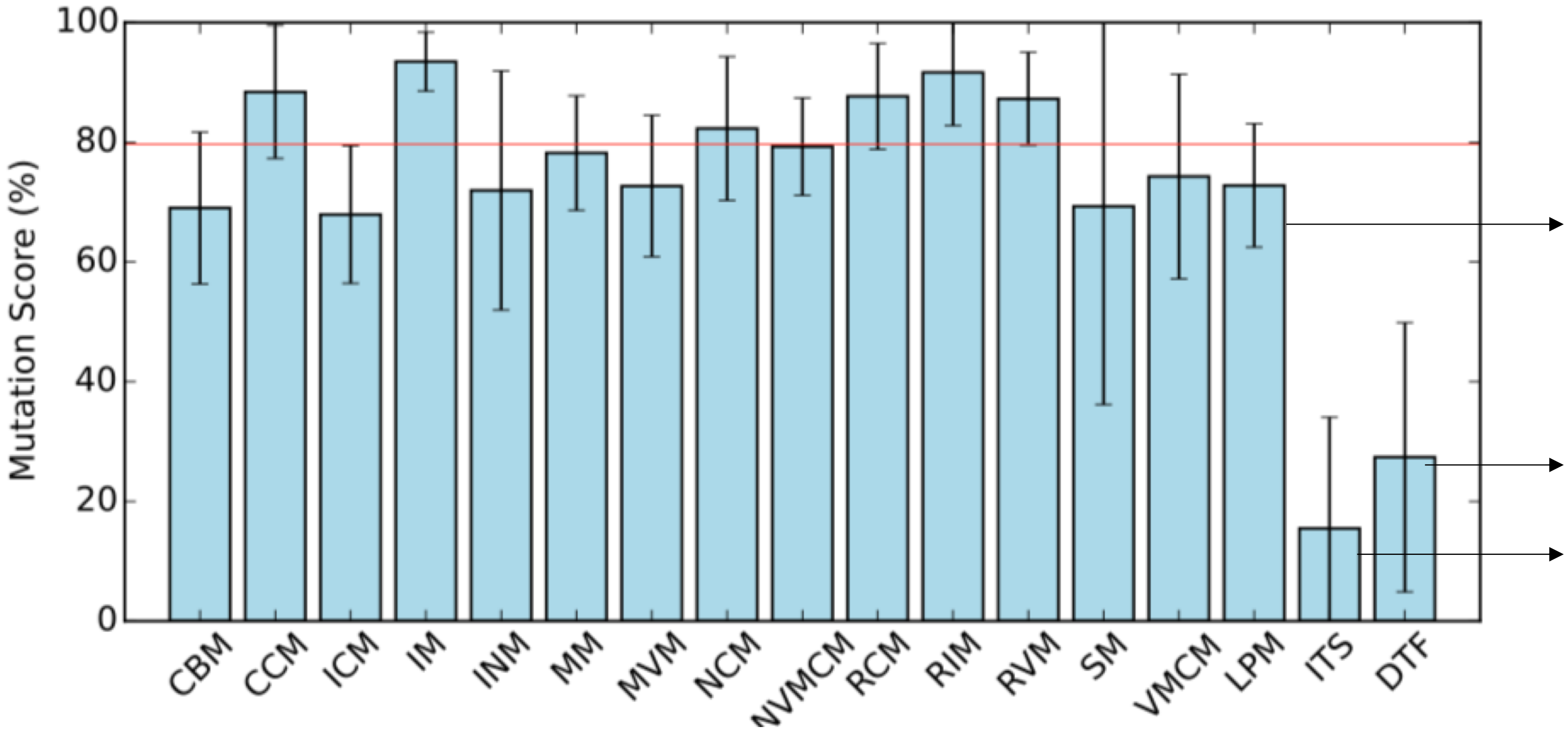
Mutation Score



79.65%

72.78%

Mutation Score



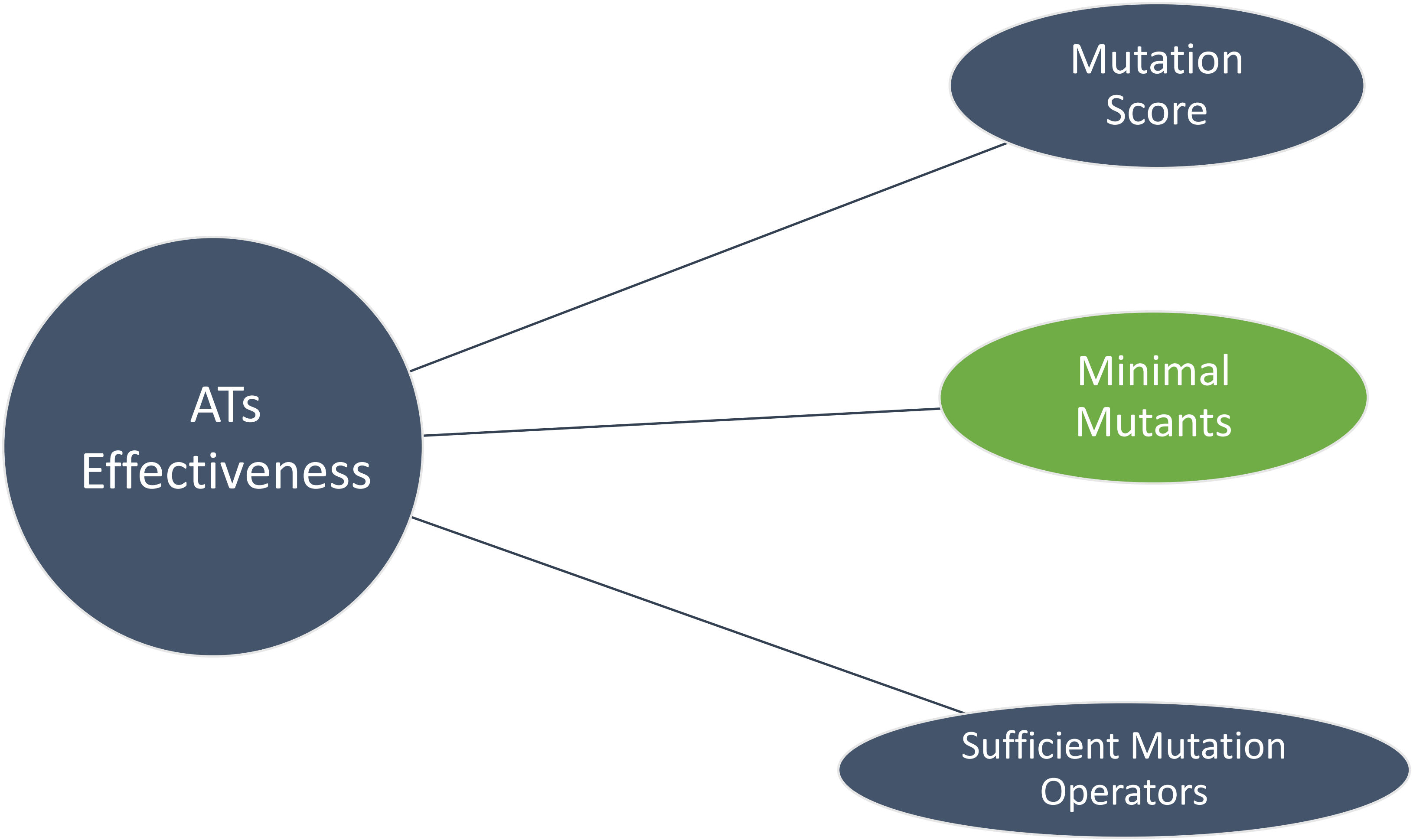
79.65%

72.78%

27.39%

15.49%

Quantitative Analysis



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Minimal Mutants

- Proxies to find the mutants that are harder to kill among the generated ones

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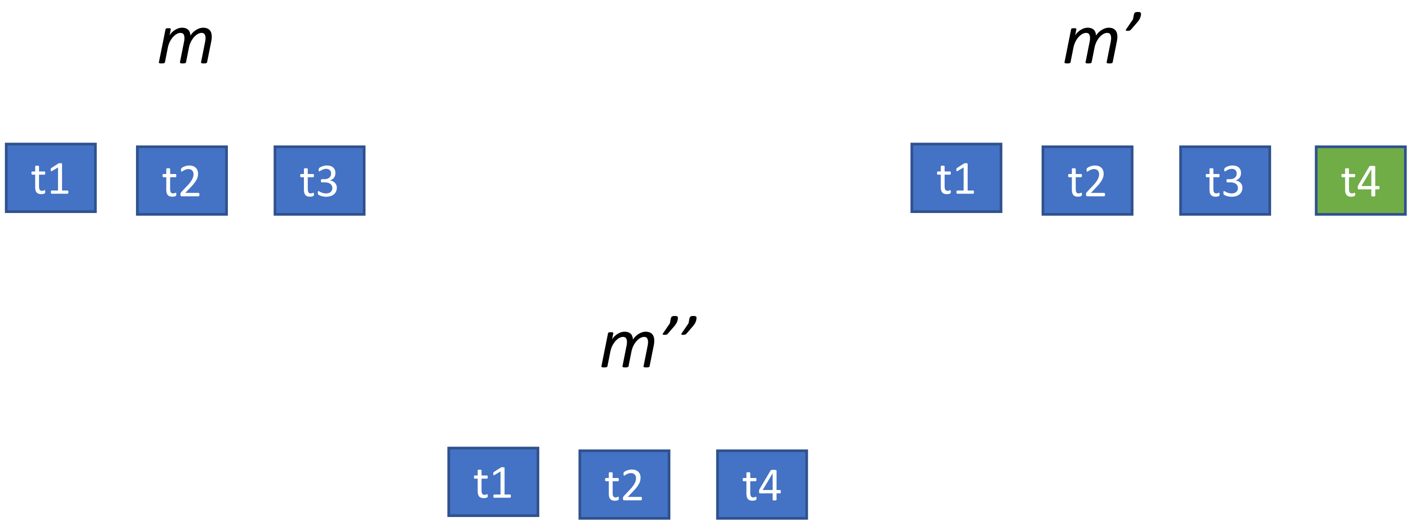
- Dynamic Subsumption:



m

t1 t2 t3

m’

t1 t2 t3 🟩t4

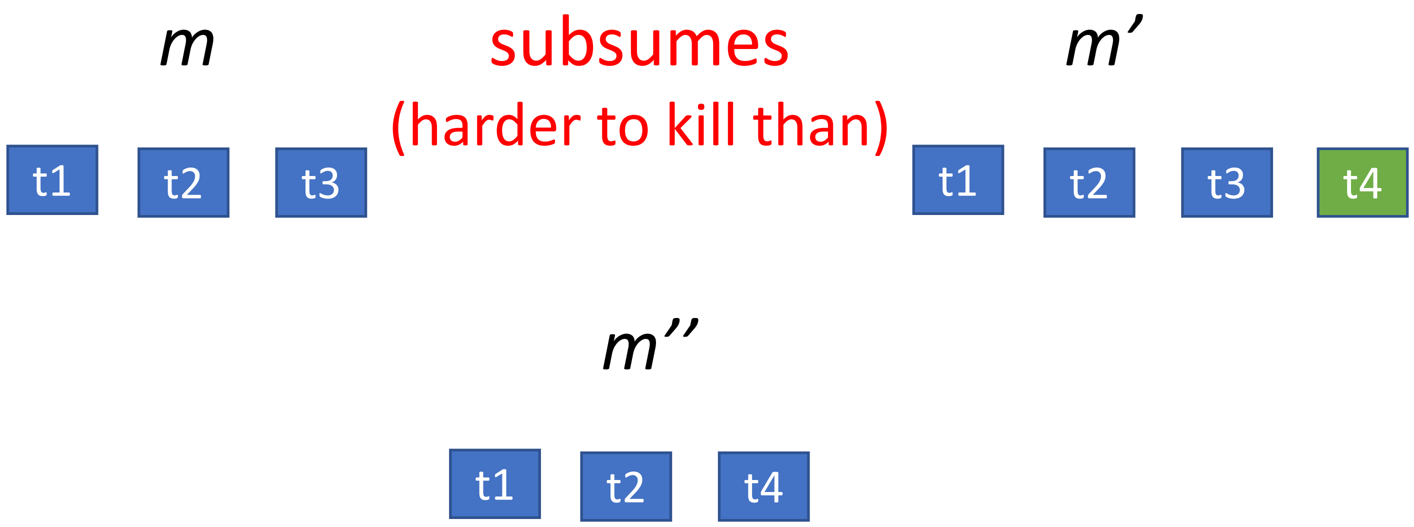
m’’

t1 t2 t4

Minimal Mutants

- Proxies to find the mutants that are harder to kill among the generated ones

- Dynamic Subsumption:



m subsumes (harder to kill than) *m’*

t1 t2 t3   t1 t2 t3 t4

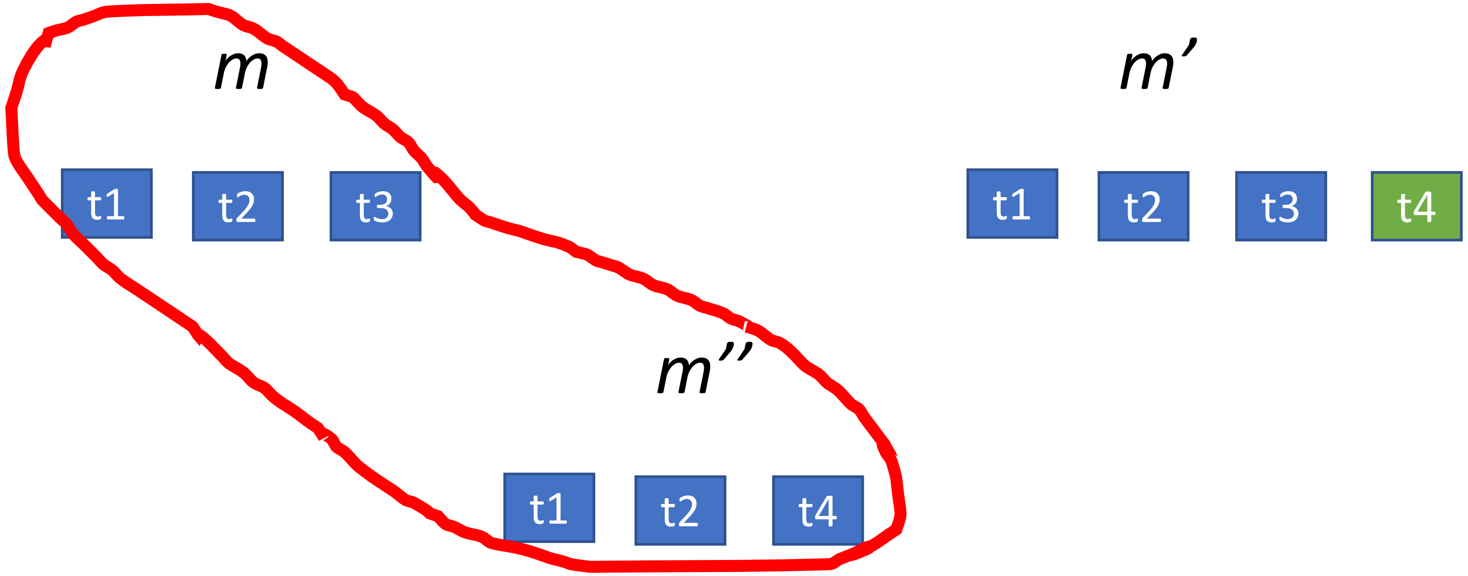
m’’

t1 t2 t4

Minimal Mutants

- Proxies to find the mutants that are harder to kill among the generated ones

- Dynamic Subsumption:



m

t1 t2 t3

m’

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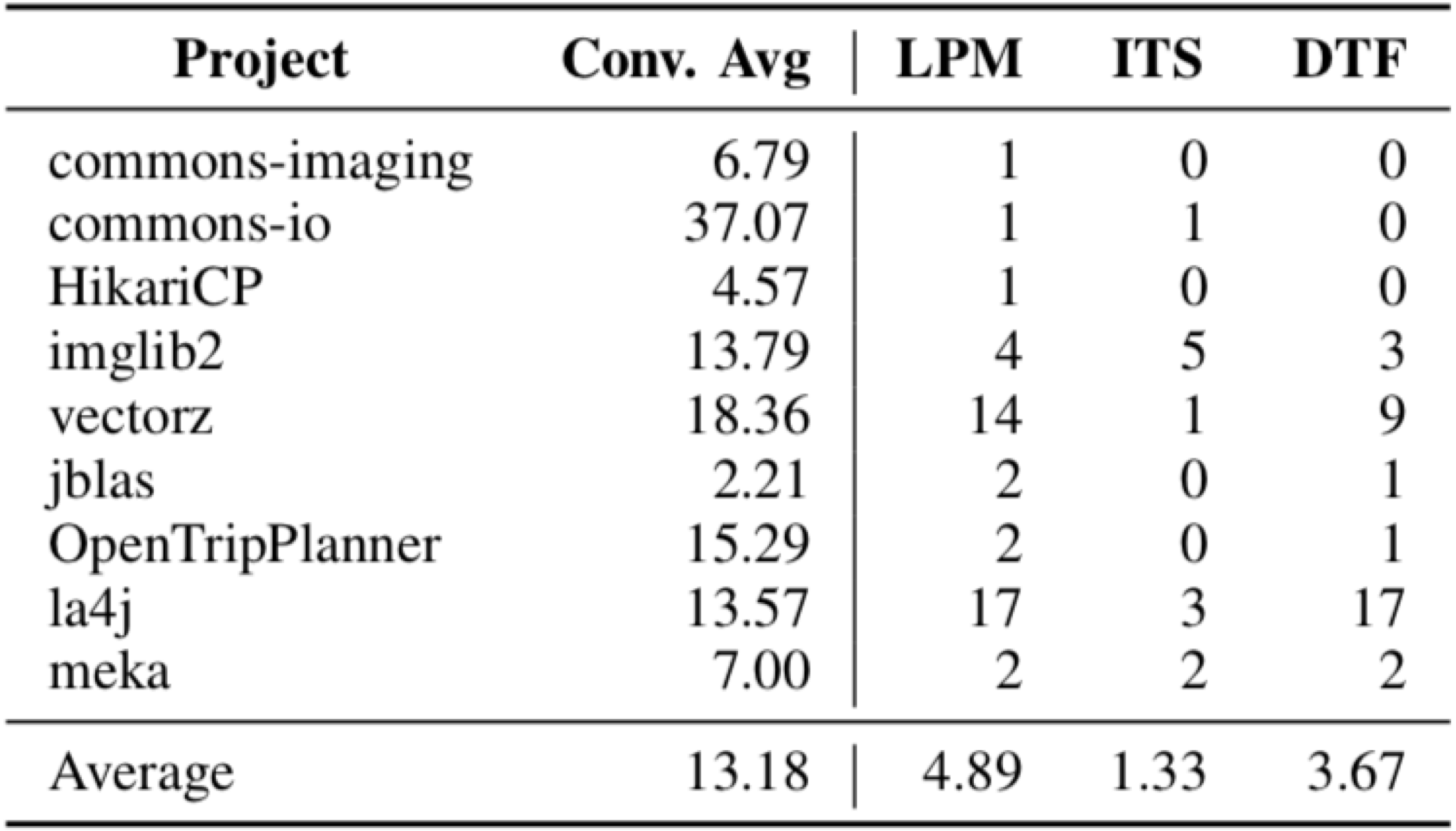
m’’

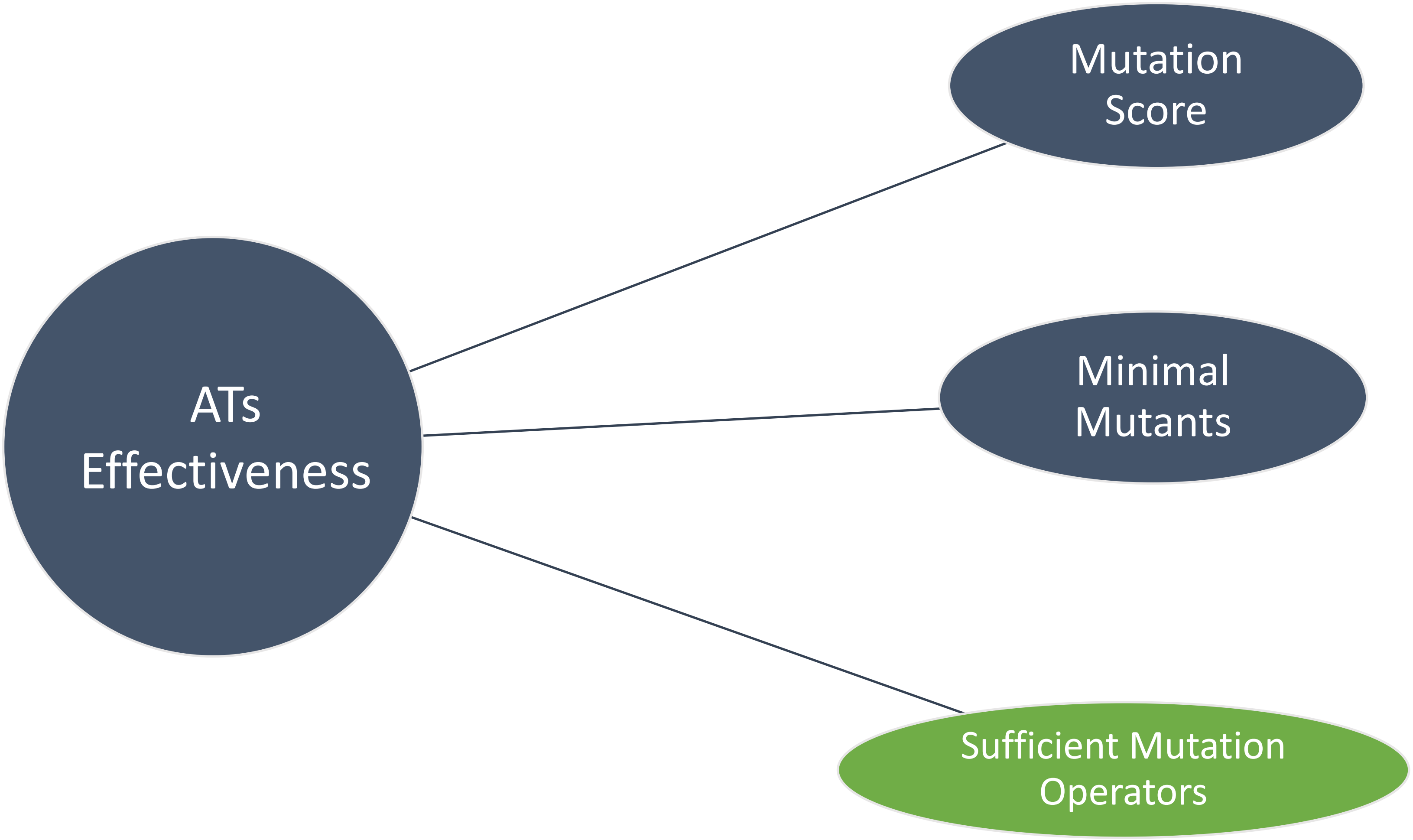
t1 t2 t4

Minimal Mutants



Project	Conv. Avg	LPM	ITS	DTF
commons-imaging	6.79	1	0	0
commons-io	37.07	1	1	0
HikariCP	4.57	1	0	0
imglib2	13.79	4	5	3
vectorz	18.36	14	1	9
jblas	2.21	2	0	1
OpenTripPlanner	15.29	2	0	1
la4j	13.57	17	3	17
meka	7.00	2	2	2
Average	13.18	4.89	1.33	3.67

Quantitative Analysis



ATs Effectiveness

Mutation Score

Minimal Mutants

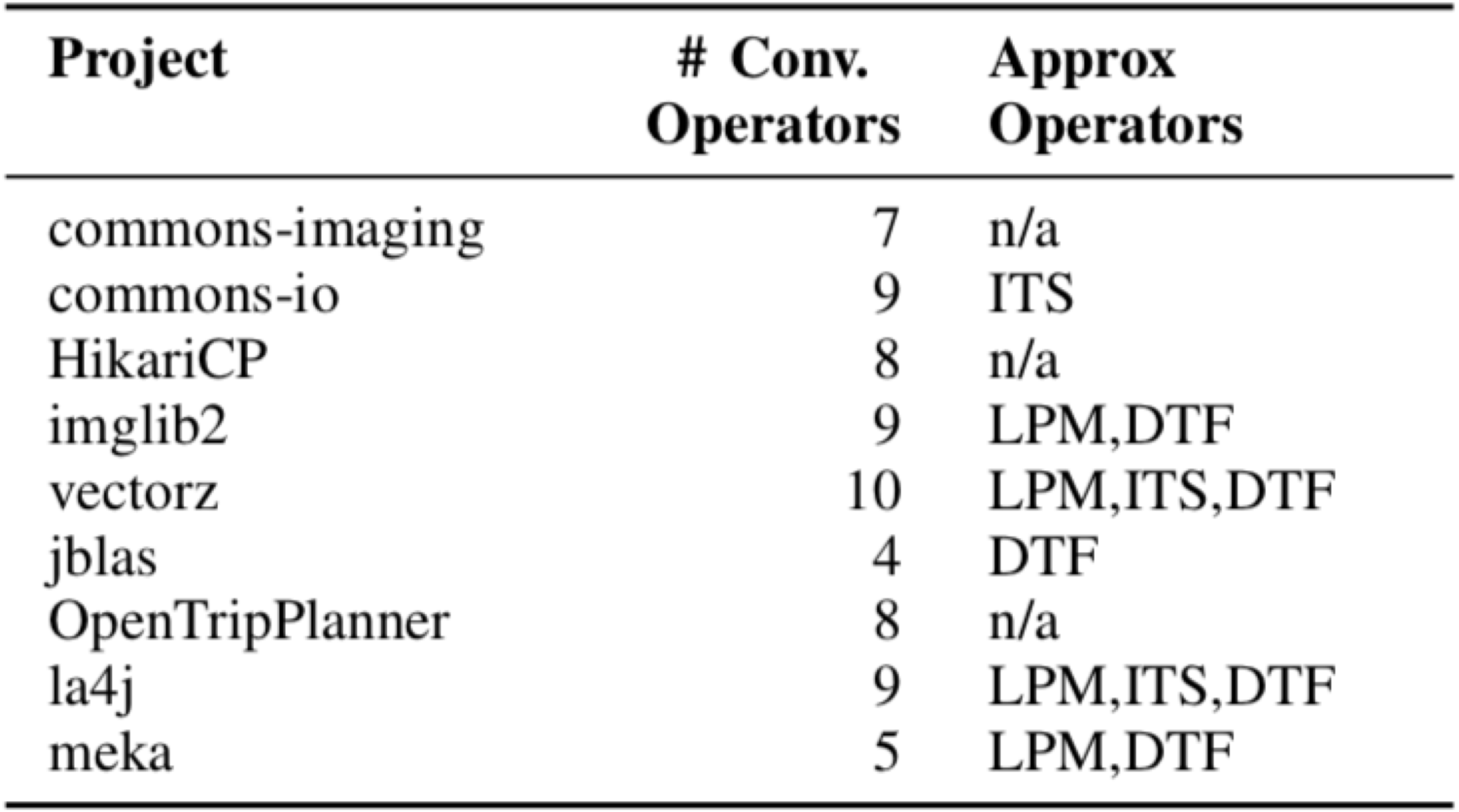
Sufficient Mutation Operators

Sufficient Mutation Operators

- *Selective mutation analysis*: heuristic for reducing the number of mutants to be run

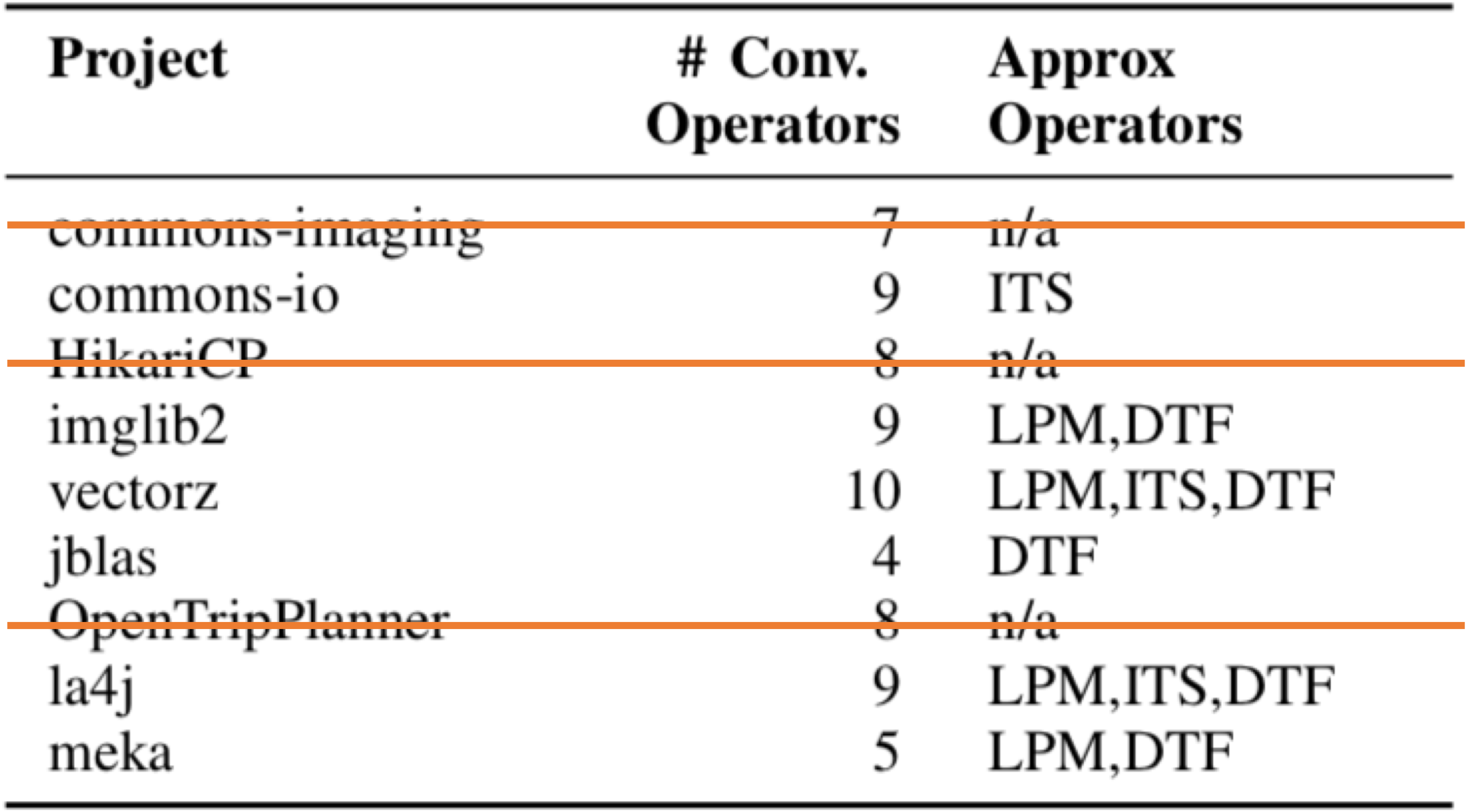
- Tests that kill mutants from the sufficient mutation operators are also sufficient to kill mutants generated by other operators

Sufficient Mutation Operators



Project	# Conv. Operators	Approx Operators
commons-imaging	7	n/a
commons-io	9	ITS
HikariCP	8	n/a
imglib2	9	LPM,DTF
vectorz	10	LPM,ITS,DTF
jblas	4	DTF
OpenTripPlanner	8	n/a
la4j	9	LPM,ITS,DTF
meka	5	LPM,DTF

Sufficient Mutation Operators



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imglib2	9	LPM,DTF
vectorz	10	LPM,ITS,DTF
jblas	4	DTF
~~OpenTripPlanner~~	~~8~~	~~n/a~~
la4j	9	LPM,ITS,DTF
meka	5	LPM,DTF

Summary of RQ1

- LPM mutants are as hard/easy to kill as mutants from conventional operators
- DTF and ITS mutation scores were low due to bad tests
- ATs generate mutants that subsume mutants from other operators
- ATs are a category of their own, not subsumed by other operators
- Results generalize beyond PIT to other mutation tools

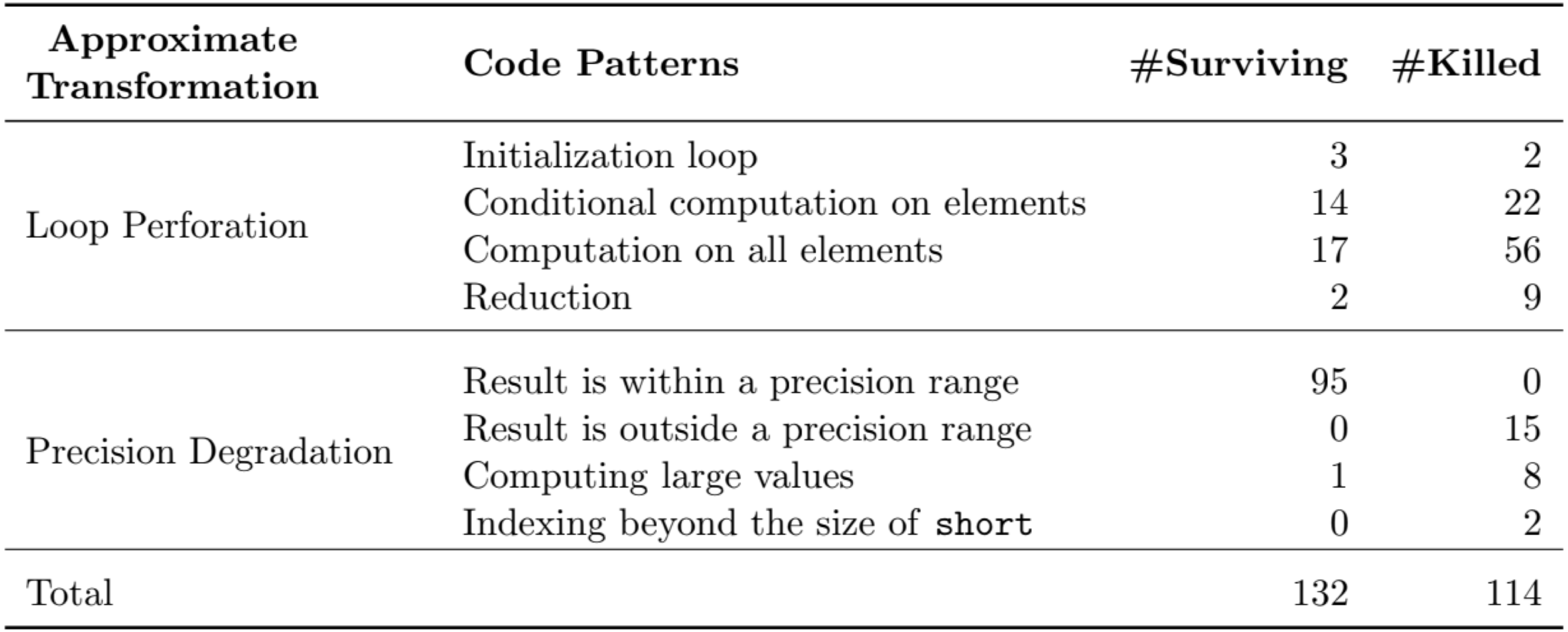
RQ2:

What code patterns do ATs as mutation operators reveal?

Qualitative Analysis

- Sampled 5% of surviving and 5% of killed LPM mutants (125 mutants)
- Sampled 1% of surviving and 1% of killed DTF and ITS mutants (121 mutants)

Code Patterns



Approximate Transformation	**Code Patterns**	**#Surviving**	**#Killed**
Loop Perforation	Initialization loop	3	2
	Conditional computation on elements	14	22
	Computation on all elements	17	56
	Reduction	2	9
Precision Degradation	Result is within a precision range	95	0
	Result is outside a precision range	0	15
	Computing large values	1	8
	Indexing beyond the size of `short`	0	2
Total		132	114

Conditional Computation on Elements Pattern

```
public int argmin() {
 if (isEmpty()) { return −1; }
 double v = Double.POSITIVE_INFINITY;
 int a = −1;
 for (int i = 0; i < length; i+=2) {
  if (!Double.isNaN(get(i)) && get(i) < v)
   v = get(i); a = i;
 }
 return a;
}
```

```
@Test
public void testArgMinMax() {
 A = new DoubleMatrix(4, 3, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0);
 assertEquals(0, A.argmin(), eps);
 …
}
```

RQ3:

How can ATs as mutation operators help software testing practice?

Practical Impact on Software Testing

- Mutation Testing Theory: Interpreting Mutation Testing Results
- Developers Community: Lessons learned, pull requests

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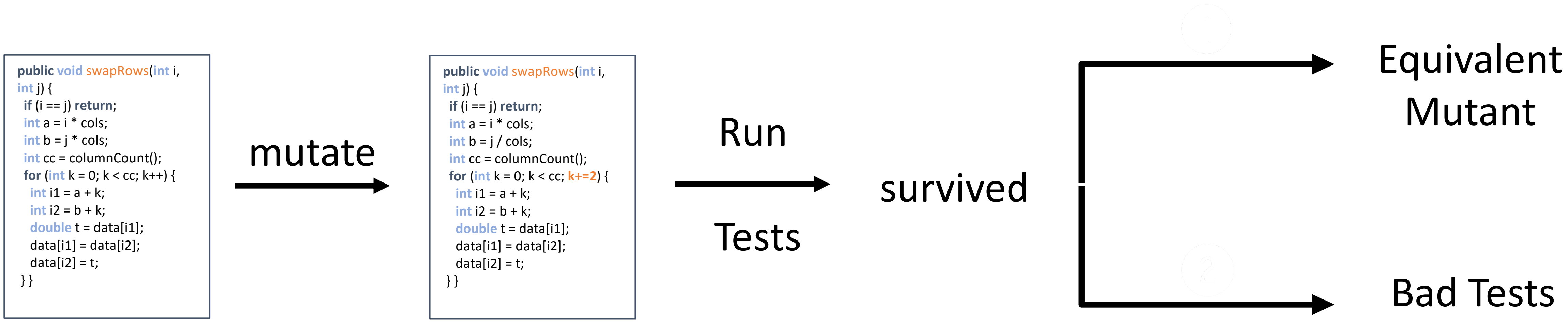
Interpreting Mutation Testing Results



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  data[i2] = t;
} }
```

mutate

```
public void swapRows(int i,
int j) {
 if (i == j) return;
 int a = i * cols;
 int b = j / cols;
 int cc = columnCount();
 for (int k = 0; k < cc; k+=2) {
  int i1 = a + k;
  int i2 = b + k;
  double t = data[i1];
  data[i1] = data[i2];
  data[i2] = t;
} }
```

Run

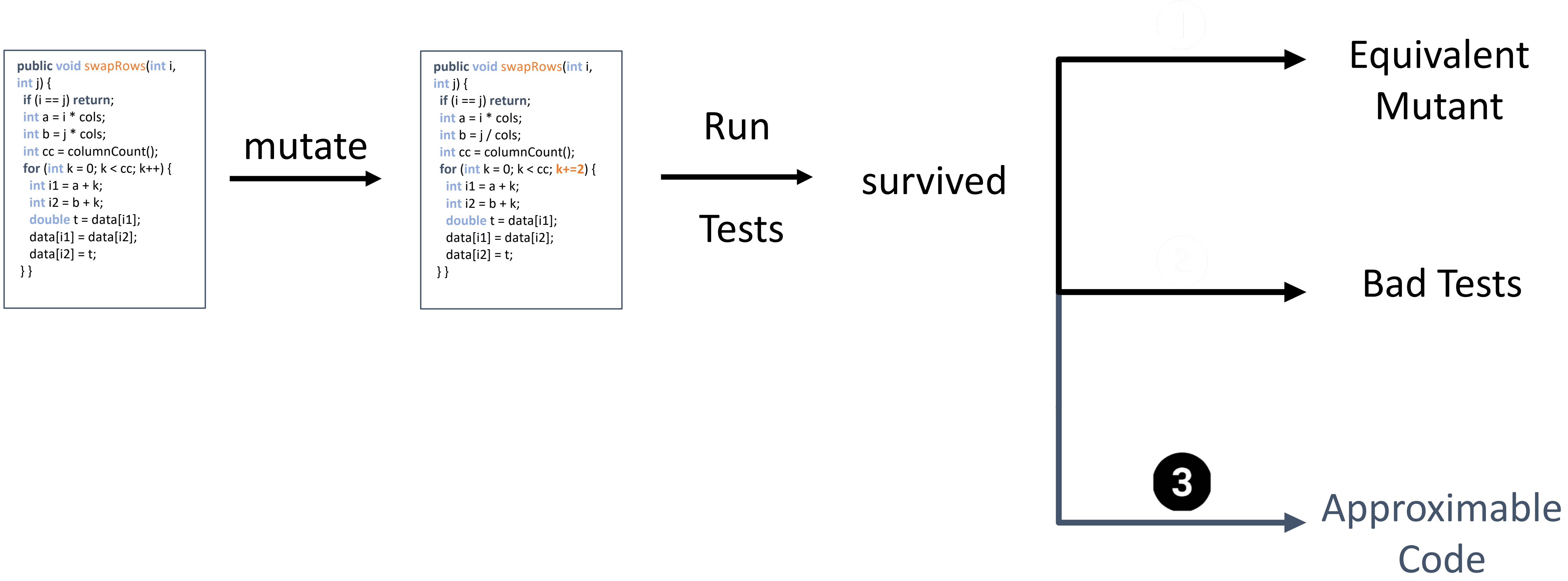
Tests

survived

Equivalent Mutant

Bad Tests

Interpreting Mutation Testing Results



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③

Approximable Code

Interpreting Mutation Testing Results

	Loop Perforation	Precision Degradation
Equivalent Mutants (%)	-	14.58
Bad Tests (%)	63.83	53.13
Approximable Code (%)	19.15	11.46
Hard to Inspect (%)	17.02	20.83

Practical Impact on Software Testing

- Mutation Testing Theory: Interpreting Mutation Testing Results
- Developers Community: Lessons learned, pull requests

Lessons (Re)Learned

1. Better loop coverage
2. Better coverage of loop condition
3. Check all output elements
4. Exercise boundary values

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2. Better coverage of loop condition
3. Check all output elements
4. Exercise boundary values

Bad Test - Pull Request Example

```
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 if (i == j) return;
 int a = i * cols;
 int b = j / cols;
 int cc = columnCount();
 for (int k = 0; k < cc; k+=2) {
  int i1 = a + k;
  int i2 = b + k;
  double t = data[i1];
  data[i1] = data[i2];
  data[i2] = t;
 } }
```

```
private void doSwapTest(AMatrix m) {
if ((m.rowCount()<2)||(m.columnCount()<2))
return;

m=m.clone();
AMatrix m2=m.clone();
m2.swapRows(0, 1);
assert(!m2.equals(m));
m2.swapRows(0, 1);
assert(m2.equals(m));
...}
```

Bad Test - Pull Request Example

```
public void swapRows(int i, int j)
{
  if (i == j) return;
  int a = i * cols;
  int b = j / cols;
  int cc = columnCount();
  for (int k = 0; k < cc; k+=2) {
    int i1 = a + k;
    int i2 = b + k;
    double t = data[i1];
    data[i1] = data[i2];
    data[i2] = t;
 } }
```

```
private void doSwapTest(AMatrix m) {
if ((m.rowCount()<2)||(m.columnCount()<2))
return;

m=m.clone();
AMatrix m2=m.clone();
m2.swapRows(0, 1);
assert(!m2.equals(m));

+ assertEquals(m2.getRow(0), m.getRow(1));
+ assertEquals(m2.getRow(1), m.getRow(0));
m2.swapRows(0, 1);
assert(m2.equals(m));
...}
```

Takeaways

- We propose ATs as mutation operators
- Our results show that:
  - ATs generate mutants that are not subsumed by conventional operators
  - ATs exercise unique code patterns
- We propose approximable code as a third way of interpreting surviving mutants
- Survived mutants inspired better testing practices (11 pull requests)